

PLASMA PROCESSING DEVICE

Field of the Invention

5 The present invention relates to a plasma processing apparatus; and more particularly, to a plasma processing apparatus for performing a predetermined process on a substrate by a plasma generation region formed by introducing a microwave into a chamber.

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Background of the Invention

 With a recent trend toward a high density and miniaturization of semiconductor devices, plasma processing
15 apparatus have been used to perform such processes as film forming, etching, ashing, and the like in a fabrication process of the semiconductor devices. Specifically, in a microwave plasma processing apparatus for producing a plasma using a microwave, the plasma can be produced stably under a
20 relatively low pressure (high vacuum) condition of about 0.1 ~ 10 Pa. Thus, the microwave plasma processing apparatus using, e.g., a microwave having a frequency of 2.45 GHz has attracted considerable attention.

 An example of such a conventional plasma processing
25 apparatus will now be explained. As shown in Fig. 6, the plasma processing apparatus includes a chamber 101

accommodating therein a substrate 111 and performing a predetermined process thereon; a high frequency power supply 105 for generating a microwave; and an antenna unit 103 for irradiating the microwave into the chamber 101.

5 The antenna unit 103 is formed of a slot plate 103c, a wave retardation plate 103b, and an antenna cover 103a. In the slot plate 103c, there are provided a plurality of slots (openings) for irradiating the microwave towards the inside of the chamber 101. The microwave generated from the high
10 frequency power supply 105 is provided to the antenna unit 103 by a waveguide 106.

 A top plate 104 serving as a part of a partition wall of the chamber 101 is disposed in an upper part of the chamber 101. The top plate 104 is made of a dielectric
15 material, e.g., a quartz. A sealing member 114, e.g., an O-ring or the like, is provided between the top plate 104 and the partition wall of the chamber 101. The antenna unit 103 is disposed above the top plate 104.

 In the chamber 101, a susceptor 107 for supporting the
20 substrate 111 accommodated therein is provided. Further, a vacuum pump 109 is connected to the chamber 101 in order to vacuum-exhaust the inside thereof.

 In the above-described plasma apparatus, the inside of the chamber 101 is exhausted to vacuum by the vacuum pump
25 109, and e.g., an argon gas is introduced into the chamber 101 as a gas for producing a plasma under a predetermined

pressure range.

As shown in Fig. 7, the microwave generated by the high frequency power supply 105 arrives at the antenna unit 103 via the waveguide 106. The microwave arriving at the antenna unit 103 propagates through the wave retardation plate 103b, as indicated by arrows, and is irradiated into the chamber 101 via the slot plate 103c to thereby generate an electromagnetic field therein.

The argon gas is dissociated by the electromagnetic field generated in the chamber 101 to thereby forming a plasma generation region 122 between the substrate 111 and the top plate 104, and thus a predetermined plasma processing is performed on the substrate 111.

In the plasma generation region 122 formed in the chamber 101, electrons and ions (charged particles) present in the plasma generation region 122 oscillate with predetermined plasma frequencies to maintain the plasma generation region 122 in an electrically neutral state. The plasma frequency tends to increase as a charge density is high and a mass of the charged particle is small.

Therefore, in the plasma generation region 122, the plasma frequency of the electron having a mass substantially smaller than that of the ion is considerably high compared to that of the ion, and it is in a microwave region. At this time, if the frequency of the microwave generated by the high frequency power supply 105 is higher than the plasma

frequency, the microwave can propagate through the plasma generation region 122 and be supplied into the plasma generation region 122.

Meanwhile, the plasma frequency of the electron is heightened as the electron density becomes high. If the plasma frequency of the electron exceeds the frequency of the microwave generated by the high frequency power supply 105, i.e., if a cutoff frequency in the plasma generation region 122 becomes higher than the frequency of the microwave, such a phenomenon is observed that an electric field of the microwave is cut off at a surface of the plasma generation region 122. Namely, the microwave is reflected by the plasma generation region 122. This phenomenon is more strongly observed as the electron density becomes higher.

Thus, the plasma density cannot be higher even though the power of the microwave is increased, so that the plasma density becomes saturated in the plasma generation region 122.

Meanwhile, the top plate 104 needs to have a certain thickness to secure a strength of the chamber 101, whose inside is depressurized and to thereby sustain the atmospheric pressure. Generally, uncontrollable standing waves 121 of the microwave are formed in the top plate 104 with such a thickness, as shown in Fig. 7. Due to the formation of such uncontrollable standing waves 121, the uniformity of the plasma density distribution becomes

deteriorated in the plasma generation region 122.

As described above, since the plasma density cannot be further increased in the plasma generation region 122 and the uniformity of the plasma density distribution cannot be further improved beyond a certain level, it is difficult to perform an efficient and uniform plasma processing on the substrate 111.

Summary of the Invention

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The present invention has been made for resolving the aforementioned problems, and it is therefore an object of the present invention to provide a plasma processing apparatus capable of increasing a plasma density and improving the uniformity of the plasma density distribution.

A plasma processing apparatus in accordance with the present invention is to perform a process on a substrate by exposing the substrate to a plasma generation region, and includes a chamber, a top plate unit and an antenna unit. The substrate is accommodated in the chamber. The top plate unit serves as a part of a partition wall of the chamber. The antenna unit supplies a high frequency electromagnetic field into the chamber to form the plasma generation region in a region between the top plate unit and the substrate accommodated in the chamber. The top plate unit contains a flat plate portion disposed to face the accommodated

substrate and being in contact with the antenna unit and a side wall portion formed to extend from a peripheral region of the flat plate portion towards a side where the substrate is disposed.

5 According to such a configuration, the side wall portion as well as the flat plate portion are formed in the top plate unit, so that a region (area) of the top plate unit facing the plasma generation region is increased. Further, since the microwave is irradiated into the chamber
10 from the side wall portion, the plasma density at the plasma generation region is enhanced.

 It is preferable that the side wall portion has a thickness of $\lambda_g/4$ or greater, wherein λ_g is a wavelength of a high frequency electromagnetic field based on a dielectric
15 constant of the top plate unit.

 By this, standing waves can be efficiently formed in the side wall portion, and the microwave having a greater power can be supplied towards a part corresponding to a periphery portion of the substrate 11 in the plasma
20 generation region 22. Further, since $\lambda_g/4$ may allow an error of $\pm 20\%$, the lowest limit of the thickness of the side wall portion 4b becomes $\lambda_g/4 \times 0.8$. The thickness of the side wall portion 4b needs to be equal to or greater than $\lambda_g/4$, because if a thickness H2 of the side wall portion 4b is
25 smaller than $\lambda_g/4$, the standing waves of the microwave cannot be formed properly in the part of the side wall

portion. Further, the clause "the flat plate portion is in contact with the antenna unit" refers to a case where the flat plate portion and the antenna unit maintain a gap therebetween, which is equal to or smaller than 1/10 of the microwave wavelength in atmosphere, and also includes a case where the flat plate portion is close contacted with the antenna unit without having a gap therebetween.

Meanwhile, in case where the thickness of the side wall portion is considerably thick, an interference pattern originating from a variation of a power density of the electromagnetic field is produced by the standing waves formed in the side wall portion, and thus the plasma becomes an unstable state. Accordingly, for suppressing the occurrence of the interference pattern as explained above and for producing a plasma stably, it is preferable that the side wall portion has a thickness smaller than λ_g .

Further, it is preferable that sides of the flat plate portion and the side wall portion facing the plasma generation region have a smooth and curved surface extending between the flat plate portion and the side wall portion.

By this, a reflection of the microwave is reduced while the microwave propagates through the top plate unit, so that the microwave efficiently propagates.

Still further, a gas injection opening for supplying a gas into the chamber is included, and it is preferable that the gas injection opening is disposed to inject the gas

along the side wall portion.

By this, the processing gas supplied along the side wall portion is dissociated efficiently by the plasma generation region to thereby contribute to the plasma processing.

Still further, it is preferable that the chamber contains a conductive portion being in contact with an outer peripheral region of the side wall portion.

By this, a part of the top plate unit not facing the plasma generation region is covered with conductors, and a reflection of the microwave is reduced while the microwave propagates through the top plate unit, so that the microwave efficiently propagates. Further, the clause "the conductive portion is in contact with the outer peripheral region of the side wall portion" refers to a case where the conductive portion and the side wall portion maintain a gap therebetween, which is equal to or smaller than $1/10$ of the microwave wavelength in atmosphere, and also includes a case where the side wall portion is close contacted with the conductive portion without having a gap therebetween.

Brief Description of the Drawings

Fig. 1 offers a cross sectional view of a plasma processing apparatus in accordance with a preferred embodiment of the present invention.

Fig. 2 is a first view showing propagation of a microwave for explaining an operation of the plasma processing apparatus in the same preferred embodiment.

Fig. 3 provides a second view showing propagation of a microwave for explaining an operation of the plasma processing apparatus in the same preferred embodiment.

Fig. 4 sets forth a view for showing a measurement result of the electron density in the plasma generation region of the plasma processing apparatus described in Fig. 2 in the same embodiment.

Fig. 5 presents another view for showing a measurement result of the electron density in the plasma generation region of the plasma processing apparatus described in Fig. 2 in the same embodiment.

Fig. 6 illustrates a cross sectional view of a conventional plasma processing apparatus.

Fig. 7 depicts a view for showing propagation of a microwave for explaining an operation of the plasma processing apparatus described in Fig. 6.

Detailed Description of the Preferred Embodiment

A plasma processing apparatus in accordance with the present invention will now be described. As shown in Fig. 1, the plasma processing apparatus includes a chamber 1 accommodating therein a substrate 11 and performing a

predetermined processing on the substrate 11; a high frequency power supply 5 for generating a microwave; and an antenna unit 3 for irradiating the microwave into the chamber 1.

5 The antenna unit 3 is comprised of a slot plate 3c, a wave retardation plate 3b, and an antenna cover 3a. The slot plate 3c is made of, e.g., a copper plate having a thickness of about 0.1 mm ~ several nm. The slot plate 3c is provided with a plurality of slots (openings) for irradiating the
10 microwave towards the inside of the chamber 1. The microwave generated from the high frequency power supply 5 is provided to the antenna unit 3 by a waveguide 6.

 In the chamber 1, a susceptor 7 for supporting the substrate 11 on which a predetermined plasma processing is
15 carried out is provided. Further, a vacuum pump 9 is connected to the chamber 1 in order to vacuum-exhaust the inside thereof.

 A top plate unit 4 serving as a part of a partition wall of the chamber 1 is disposed in an upper part of the
20 chamber 1. The top plate unit 4 is made of a dielectric material, e.g., a quartz. A sealing member 14, e.g., an O-ring, is provided between the top plate unit 4 and the partition wall of the chamber 1. The antenna unit 3 is disposed above the top plate unit 4.

25 Particularly, the top plate unit 4 has a flat plate portion 4a and a side wall portion 4b. The flat plate

portion 4a is disposed to face the accommodated substrate 11 and is in contact with the slot plate 3c. The side wall portion 4b is formed to extend from a peripheral region of the flat plate portion 4a towards a side where the substrate 11 is disposed. An outer peripheral surface of the side wall portion 4b is in contact with the chamber 1.

Sides of the flat plate portion 4a and the side wall portion 4b facing the plasma generation region have a smooth and curved surface extending between the flat plate portion 4a and the side wall portion 4b. Hereinafter, the top plate unit 4 having the flat plate portion 4a and the side wall portion 4b is referred to as a bell jar type top plate unit 4, in contrast with a conventional flat plate type top plate unit having only a flat plate portion.

A thickness H1 of the side wall portion 4b is equal to or greater than $\lambda_g/4$, wherein λ_g is a wavelength of the microwave based on a dielectric constant of the top plate unit 4. The wavelength λ_g of the microwave propagating through the top plate unit 4 is about 60 mm, given that the wavelength of the microwave is 2.45 GHz and the dielectric constant of the top plate unit 4 made of, e.g., a quartz is taken into consideration. Therefore, it is preferable that the thickness H1 of the side wall portion 4b is equal to or greater than about 15 mm which corresponds to 1/4 of the wavelength λ_g of the microwave.

Here, $\lambda_g/4$ may allow an error of $\pm 20\%$. As a result,

the lowest limit of the thickness H1 of the side wall portion 4b becomes $\lambda_g/4 \times 0.8$ (about 12 mm).

The thickness H1 of the side wall portion 4b needs to be equal to or greater than $\lambda_g/4$ as mentioned above, because
5 if a thickness H2 of the side wall portion 4b is smaller than $\lambda_g/4$, as shown in Fig. 3, standing waves of the microwave that will be discussed later cannot be formed properly in the part of the side wall portion 4b.

On the other hand, if the thickness H1 of the side
10 wall portion 4b is considerably thick, an interference pattern originating from a variation of a power density of the electromagnetic field is produced by the standing waves formed in the side wall portion 4b. If the plasma density is varied to be greater than an intrinsic plasma density of the
15 plasma processing apparatus, the interference pattern is changed to a difference interference pattern, so that two interference patterns which are different each other appear in the vicinity of the intrinsic plasma density.

The occurrence of two different interference patterns
20 results in the variation of the interference pattern, and further, makes the plasma generation unstable, and hence the number of interference patterns needs to be small. The number of interference patterns largely depends on the thickness H1 of the side wall portion 4b, and increases as
25 the thickness H1 of side wall portion 4b becomes large to thereby rapidly increase roughly every integer multiple of λ

$\lambda_g/2$.

For enhancing the plasma density by the side wall portion 4b, the thickness H1 of the side wall portion 4b is preferably equal to or greater than $\lambda_g/4$ as mentioned above, and, more preferably, around $\lambda_g/2$.

However, it is not necessary that the thickness H1 of the side wall portion 4b is equal to or greater than twice of $\lambda_g/2$, i.e., λ_g . And, it is preferable that the thickness H1 of the side wall portion 4b is smaller than λ_g in order to reduce the number of interference patterns to thereby stably produce the plasma.

Further, the clause "the flat plate portion 4a is in contact with the slot plate 3c" refers to a case where the flat plate portion 4a and the slot plate 3c maintain a gap therebetween, which is equal to or smaller than $1/10$ of the microwave wavelength in atmosphere, and also includes a case where the flat plate portion 4a is close contacted with the slot plate 3c without having a gap therebetween.

In the same manner, the clause "the side wall portion 4b is in contact with the chamber 1" refers to a case where the side wall portion 4b and the chamber 1 maintain a gap L therebetween, which is equal to or smaller than $1/10$ of the microwave wavelength in atmosphere, and also includes a case where the side wall portion 4b is close contacted with the chamber 1 without having a gap therebetween.

The gap is configured to be equal to or smaller than

1/10 of the microwave wavelength as described above, because distribution of the electromagnetic field inside the top plate unit 4 is changed by the electromagnetic field generated in the gap, if there is a gap greater than 1/10 of the microwave wavelength.

Next, a plasma processing by the above-described plasma apparatus will be discussed. First, the inside of the chamber 1 is exhausted to vacuum by the vacuum pump 9, and a gas, e.g., an argon gas, for producing a plasma under a predetermined pressure range is introduced into the chamber 1.

Meanwhile, the microwave is generated by the high frequency power supply 5. The generated microwave arrives at the antenna unit 3 through the waveguide 6. The microwave arriving at the antenna unit 3 propagates inside the wave retardation plate 3b towards the periphery thereof, as indicated by arrows. The microwave propagating through the wave retardation plate 3b is irradiated into the chamber 1 through the slot plate 3c, as indicated by the arrows. By the microwave irradiated into the chamber 1, the electromagnetic field is generated in the chamber 1.

The argon gas is ionized by the electromagnetic field generated in the chamber 1, and the plasma generation region 22 is formed between the substrate 11 and the top plate unit 4. If a processing gas is introduced into the plasma generation region 22, it is dissociated, whereby a

predetermined plasma processing is performed on the substrate 11.

In the aforementioned plasma processing apparatus, the top plate unit 4 is of a bell jar type and is provided with the side wall portion 4b in addition to the flat plate portion 4a are formed, so that a region (area) of the top plate unit 4 facing the plasma generation region 22 is increased.

In a conventional plasma processing apparatus, there is a limitation on the enhancement of the plasma density in the plasma generation region since the microwave is irradiated only from the flat plate portion. Since, however, the microwave is irradiated from the side wall portion 4b as well as from the flat plate portion 4a towards the inside of the chamber 1 in the present plasma processing apparatus, the microwave irradiated from the side wall portion 4b can contribute to the improvement of the plasma density in the plasma generation region 22.

As a result, the plasma density in the plasma generation region 22 is further improved in the present plasma processing apparatus, and thus, the plasma processing can be performed more efficiently.

Particularly, in the present plasma processing apparatus, the side wall portion 4b has the thickness H1 equal to or greater than $\lambda_g/4$, wherein λ_g is the wavelength of the microwave based on the dielectric constant of the top

plate unit 4. Accordingly, the standing waves 21 can be formed in the side wall portion 4b as shown in Fig. 2.

Meanwhile, by setting the thickness H1 of the side wall portion 4b to be smaller than λ_g , the number of interference patterns produced in the side wall portion 4b is reduced and thus the plasma can be produced stably.

Further, the flat plate portion 4a is in contact with the slot plate 3c, and the outer peripheral surface of the side wall portion 4b is in contact with the chamber 1. Accordingly, a part of the top plate unit 4 not facing the plasma generation region 22 is covered with conductors. Therefore, a reflection of the microwave is reduced while the microwave propagates through the top plate unit, so that the microwave efficiently propagates.

Still further, sides of the flat plate portion 4a and the side wall portion 4b facing the plasma generation region have a smooth and curved surface extending between the flat plate portion 4a and the side wall portion 4b. As a result, reflection of the microwave is suppressed when the microwave propagates from the flat plate portion 4a to the side wall portion 4b, so that the microwave efficiently propagates to the side wall portion 4b.

By doing this, the standing waves 21 are efficiently formed in the side wall portion 4b by the microwave propagated thereto, and the microwave having a greater power can be supplied towards a part corresponding to a periphery

portion of the substrate 11 in the plasma generation region 22. As a result, the plasma density in the plasma generation region 22 can be increased and, at the same time, the uniformity of the plasma density is further improved, whereby the plasma processing can be performed more uniformly on the substrate 11.

Meanwhile, in case where the side wall portion 4b has a thickness H_2 smaller than $\lambda_g/4$, as shown in Fig. 3, standing waves cannot be formed certainly in the side wall portion 4b. In this case, the microwave having a greater power cannot be supplied towards the part corresponding to the periphery portion of the substrate 11 in the plasma generation region 22, and the plasma density in the plasma generation region 22 cannot be increased sufficiently.

Subsequently, measurement and evaluation of the plasma density (electron density) for the above-described plasma processing apparatus will now be discussed. First, the plasma generation region was formed inside the plasma processing apparatus under a condition of 2 KW of microwave power, 67 Pa of pressure, 1.7 Pa·m³/sec of argon flow rate, and 0.034 Pa·m³/sec of nitrogen flow rate.

The electron density in the plasma generation region was measured using a Langmuir probe. Further, the electron density of the conventional plasma processing apparatus (flat plate type) was measured as a reference in the same manner.

The results are shown in Fig. 4. The horizontal axis, represents a distance from a position corresponding to the center of the substrate towards the outer periphery of the substrate. The vertical axis represents the electron density, specifically, shows values where the electron density at the position corresponding to the center of the substrate is normalized as 1.

As shown in Fig. 4, it can be noted that the electron density in the plasma generation region of the conventional plasma processing apparatus decreases gradually from the center of the substrate towards the outer side.

On the other hand, the present plasma processing apparatus exhibits a trend that the electron density gradually increases from a position spaced apart from the position corresponding to the center of the substrate by about 150 mm. From this, it was verified that the microwave having a greater power is supplied towards the part corresponding to the periphery portion of the substrate in the plasma generation region 22, whereby the electron density can be increased.

The above can also be constructed in a different manner as follows. First, in the conventional plasma processing apparatus, the microwave is irradiated from the flat plate type top plate 104 into the plasma generation region 122, as shown in Fig. 7. Thus, the boundary condition is configured such that the microwave is supplied only from

the outer periphery of the top plate 104 into the part corresponding to the periphery portion of the substrate 111 in the plasma generation region 122, and the plasma generation region 122 disappears at the side portion of the chamber 101.

In contrast, in the present plasma processing apparatus, the microwave is also supplied from the side wall portion 4b (side portion of the chamber 1) towards the part corresponding to the periphery portion of the substrate 11 in the plasma generation region 22, by the standing waves 21 formed in the side wall portion 4b of the bell jar type top plate unit 4. Therefore, the boundary condition is configured such that the plasma generation region 22 is generated at the side wall portion 4b.

As a result, in the present plasma processing apparatus, it is possible to readily increase the electron density (plasma density) of the plasma generation region compared with the conventional plasma processing apparatus and, at the same time, enhance the uniformity of the electron density. Further, it is possible to perform a predetermined plasma processing on the substrate efficiently and uniformly.

The inventors adjusted the size of, e.g., the top plate unit 4 based on the evaluation results and carried out the plasma density measurement again. The measurement results will now be discussed. First, the plasma generation

region was formed inside the plasma processing apparatus under the condition of 1.5 KW of microwave power, 67 Pa of pressure, 1.7 Pa·m³/sec of argon flow rate, and 0.068 Pa·m³/sec of nitrogen flow rate.

5 Fig. 5 describes measurement results of the electron density in the plasma generation region, which was measured by using the Langmuir probe. As shown in Fig. 5, it can be seen that the electron densities in the plasma generation regions of the present and the conventional plasma
10 generation device gradually decrease from the center of the substrate towards the outer side thereof.

 However, it was observed that the electron density in the present plasma processing apparatus decreases more slowly from the center of the substrate towards the outer
15 side thereof than that in the conventional plasma processing apparatus.

 Thus, it can be seen that the variation of the electron density along the diametric direction of the wafer can be suppressed, and thus the plasma density can be
20 further uniformed, compared with the conventional plasma processing apparatus.

 Further, since the boundary condition is configured such that the plasma generation region 22 is generated at the side wall portion 4b of the present plasma processing
25 apparatus (side portion of the chamber 1), it is preferable that gas injection openings for a processing gas and the

like are disposed to inject the gas along the side wall portion 4b, as shown in Fig. 2. By doing this, the processing gas supplied along the side wall portion 4b is dissociated efficiently by the plasma generation region to
5 thereby contribute to the plasma processing.

It is to be appreciated that the above-described embodiment is a mere example and thus should not be constructed to be limited thereto. The present invention is defined not by the aforementioned explanations but by claims,
10 and it will be understood that various changes and modifications can be made without departing from the spirit and scope of the invention as defined in the following claims.

In accordance with the plasma processing apparatus of
15 the present invention, the side wall portion as well as the flat plate portion are formed in the top plate unit, so that a region (area) of the top plate unit facing the plasma generation region is increased. Further, since the microwave is irradiated into the chamber from the side wall portion,
20 the plasma density at the plasma generation region is enhanced.

Given that the wavelength of the microwave based on the dielectric constant of the top plate unit is λ_g , it is preferable that the thickness of the side wall portion is
25 equal to or greater than $\lambda_g/4$. By doing this, it is possible to supply the microwave having a greater power to the part

of the plasma generation region corresponding to the outer periphery of the substrate.

Meanwhile, in case where the thickness of the side wall portion is considerably thick, an interference pattern
5 originating from a variation of a power density of the electromagnetic field is produced by the standing waves formed in the side wall portion, and thus the plasma becomes an unstable state. Accordingly, for suppressing the occurrence of the interference pattern as explained above
10 and for producing a plasma stably, it is preferable that the side wall portion has a thickness smaller than λ_g .

Further, it is preferable that sides of the flat plate portion and the side wall portion facing the plasma generation region have a smooth and curved surface extending
15 between the flat plate portion and the side wall portion. By doing this, reflection of the microwave is reduced while the microwave is provided from the flat plate portion to the side wall portion, so that the microwave efficiently propagates to the side wall portion.

20 Still further, it is preferable that the gas injection openings for flowing a predetermined gas to the chamber are included and disposed to inject the gas along the side wall portion. By doing this, the processing gas provided along the side wall portion is dissociated efficiently by the
25 plasma generation region to thereby contribute to the plasma processing.

Still further, it is preferable that the chamber contains a conductive portion being in contact with the outer periphery of the side wall portion. By this, in the top plate unit, a part not facing the plasma generation
5 region is covered with the conductors, so that reflection of the microwave is reduced while the microwave is provided by the top plate unit and thus efficiently propagates.

[Industrial Applicability]

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The present invention is effectively used in a structure for improving an uniformity of a plasma density distribution, in plasma processing apparatus performing on a substrate such predetermined plasma processes as etching, ashing and
15 the like, by a plasma generation region formed by introducing a microwave into a chamber.